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**Lazar et al.**

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(54) **NONLINEAR CONTROL OF LOUDSPEAKER SYSTEMS WITH CURRENT SOURCE AMPLIFIER**

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**H04R 9/06** (2006.01)  
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(52) **U.S. Cl.**  
CPC ..... **H04R 29/001** (2013.01); **H04R 3/04** (2013.01); **H04R 9/06** (2013.01); **H03F 3/183** (2013.01); **H03F 2200/03** (2013.01)

(57) **ABSTRACT**

(58) **Field of Classification Search**  
CPC ..... H04R 29/001; H04R 3/04; H04R 9/06; H03F 2200/03; H03F 3/183  
USPC ..... 381/59  
See application file for complete search history.

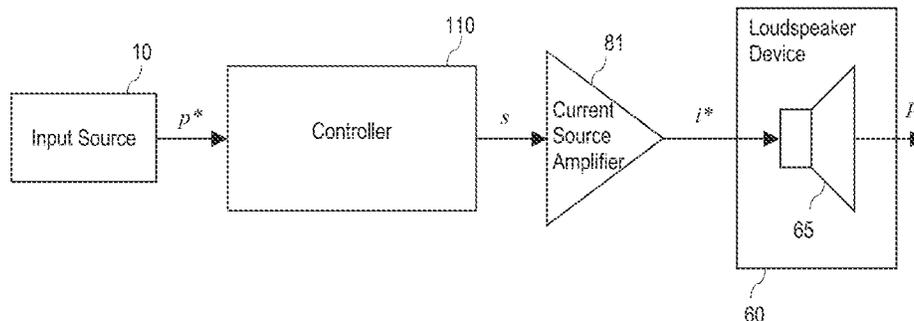
One embodiment provides a system for nonlinear control of a loudspeaker. The system comprises a current source amplifier connected to the loudspeaker, and a controller connected to the current source amplifier. The controller is configured to determine a target displacement of a diaphragm of the speaker driver based on a source signal for reproduction via the loudspeaker, determine a control current based on the target displacement of the diaphragm and a first physical model of the loudspeaker, and transmit a control current signal specifying the control current to the current source amplifier. The current source amplifier outputs the control current to drive the speaker driver based on the control current signal. An actual displacement of the diaphragm during the reproduction of the source signal is controlled based on the control current, via the control current signal.

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**20 Claims, 16 Drawing Sheets**



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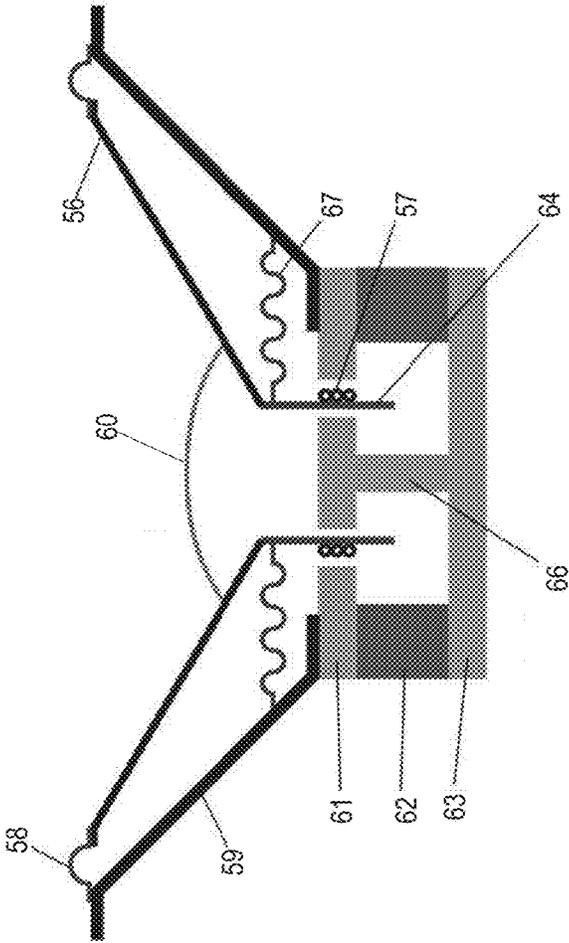


FIG. 1

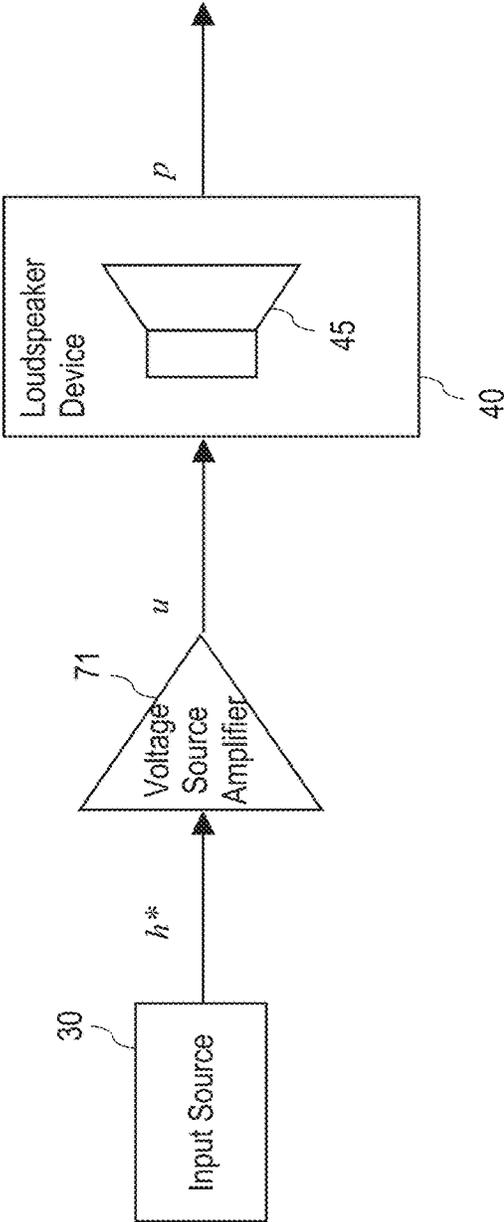


FIG. 2

70

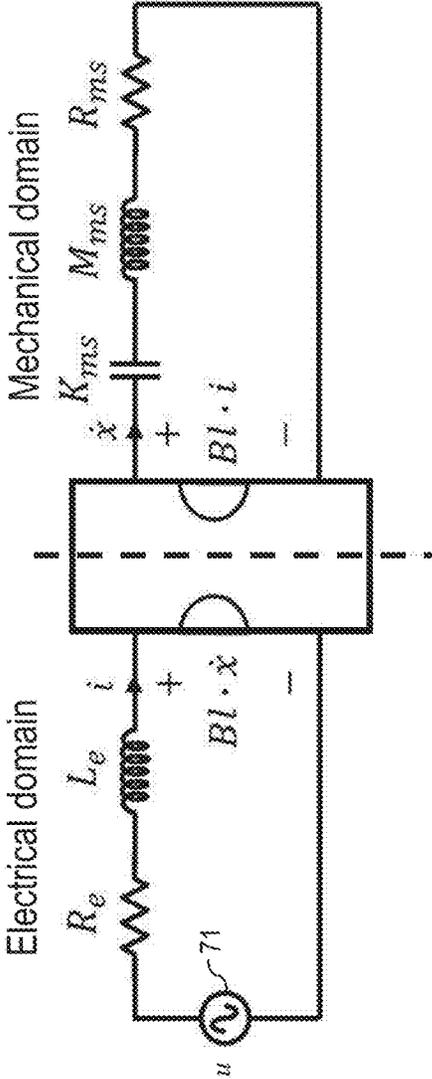


FIG. 3

150

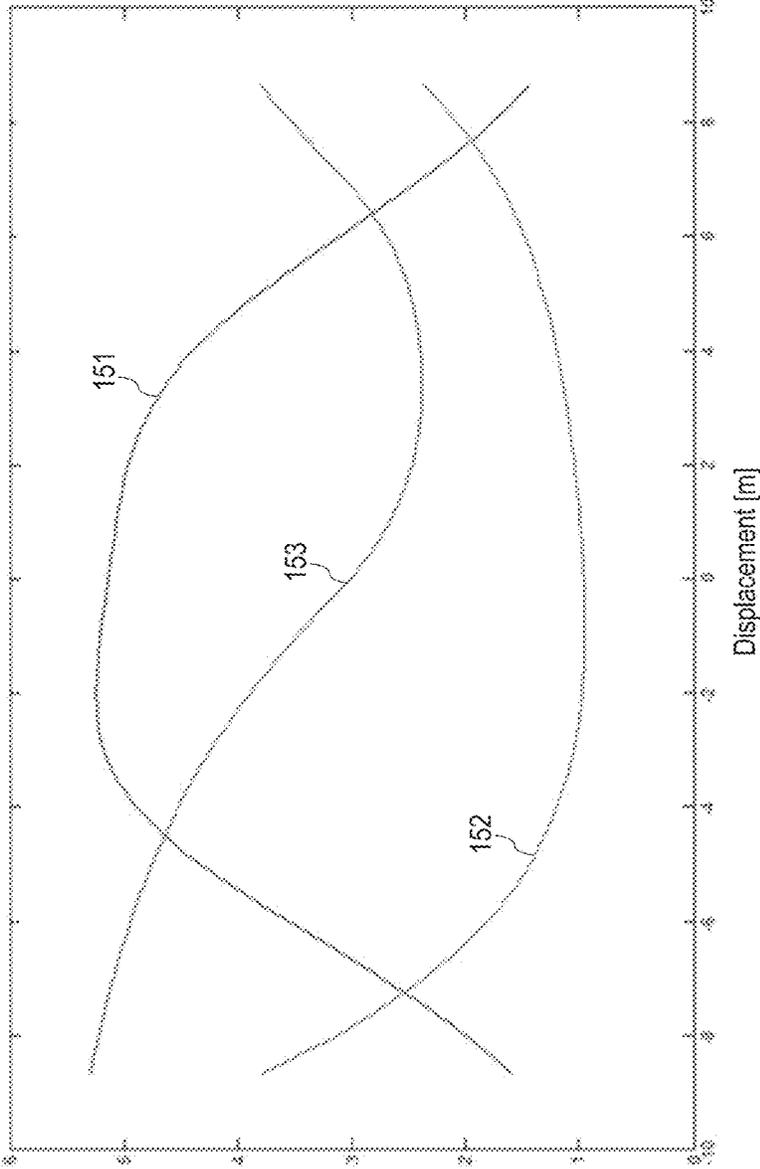


FIG. 4

400

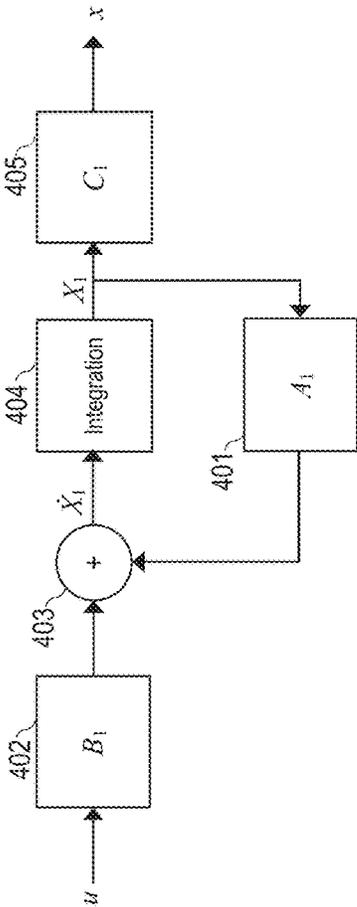


FIG. 5A

450

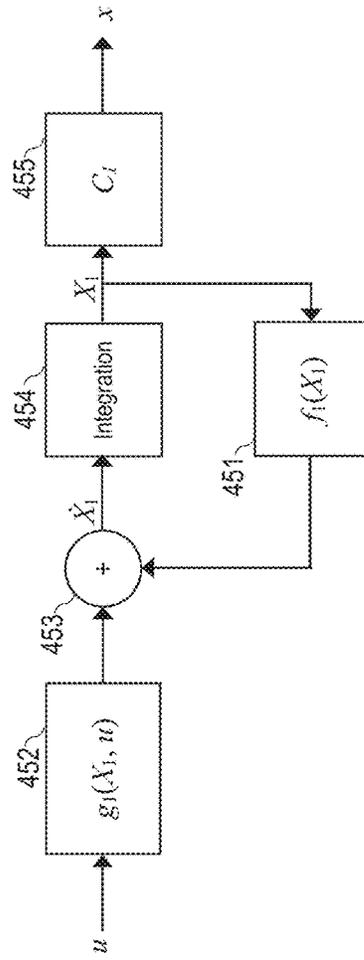


FIG. 5B

100

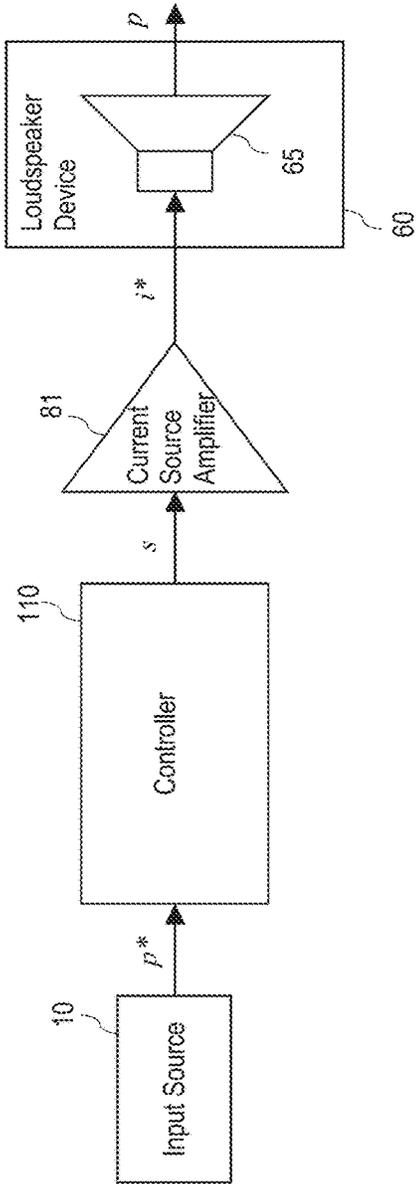


FIG. 6

80

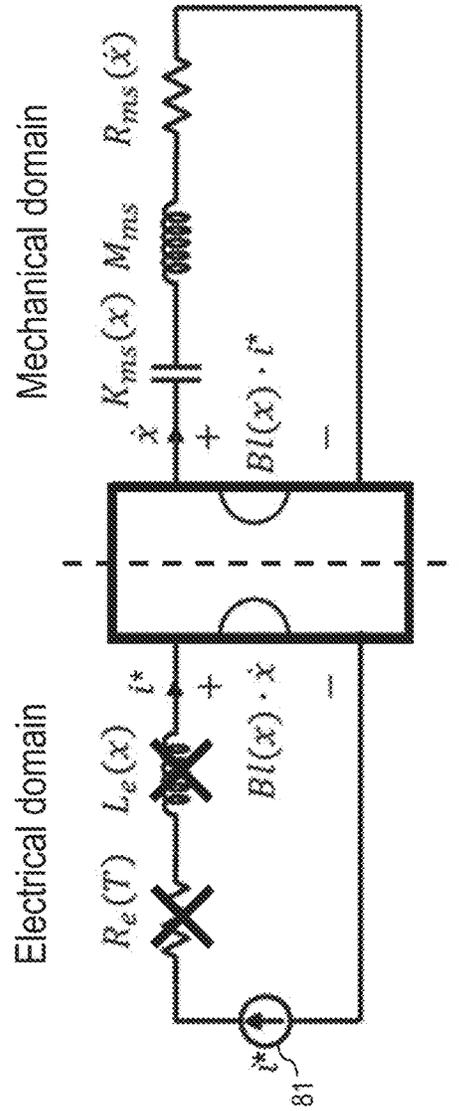


FIG. 7

410

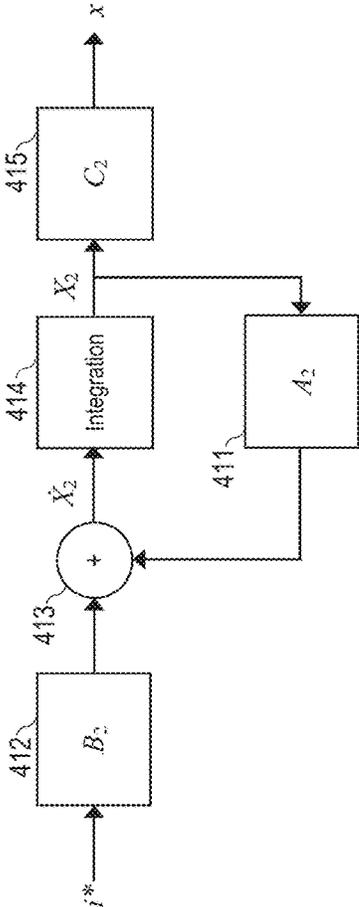


FIG. 8A

460

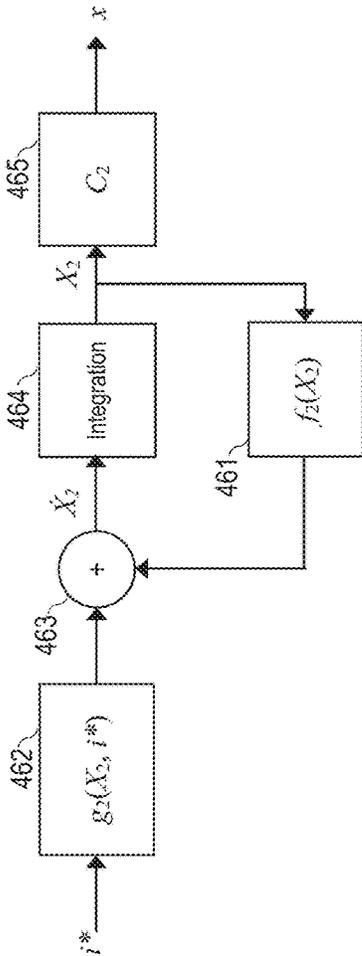


FIG. 8B

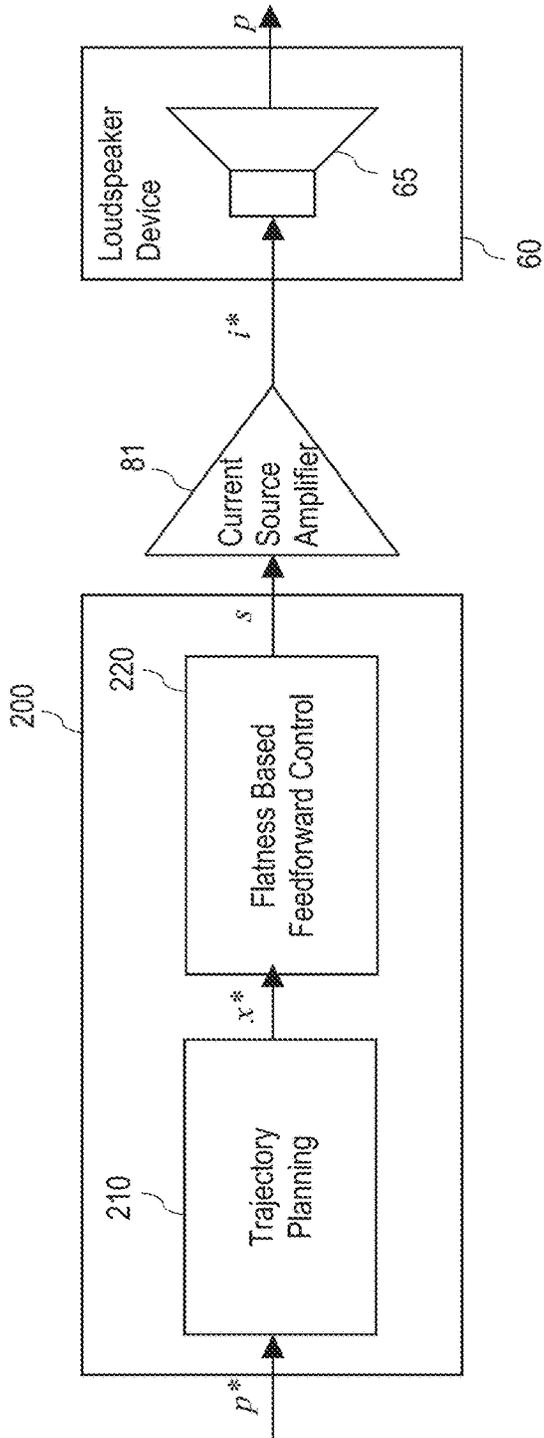


FIG. 9

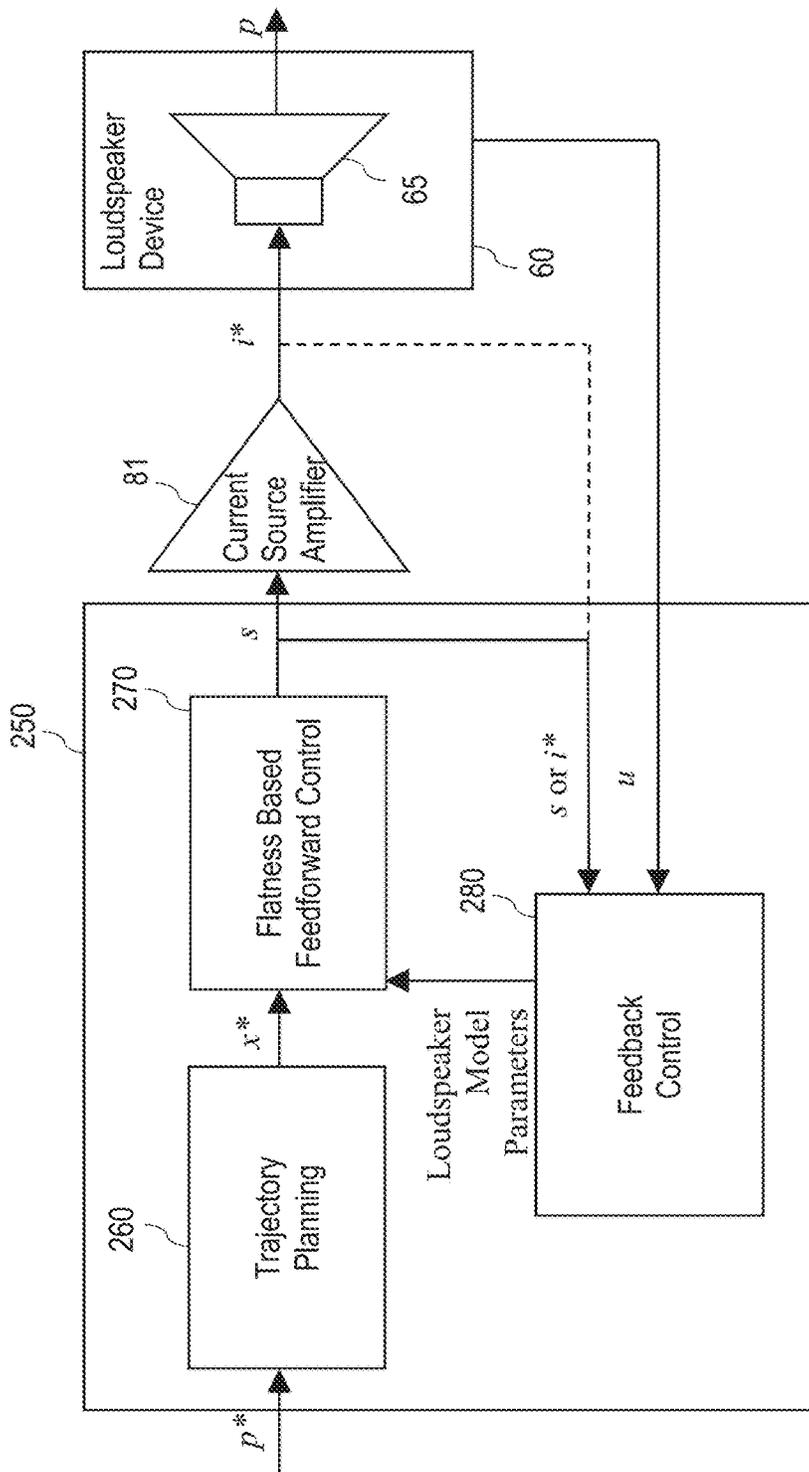


FIG. 10

500

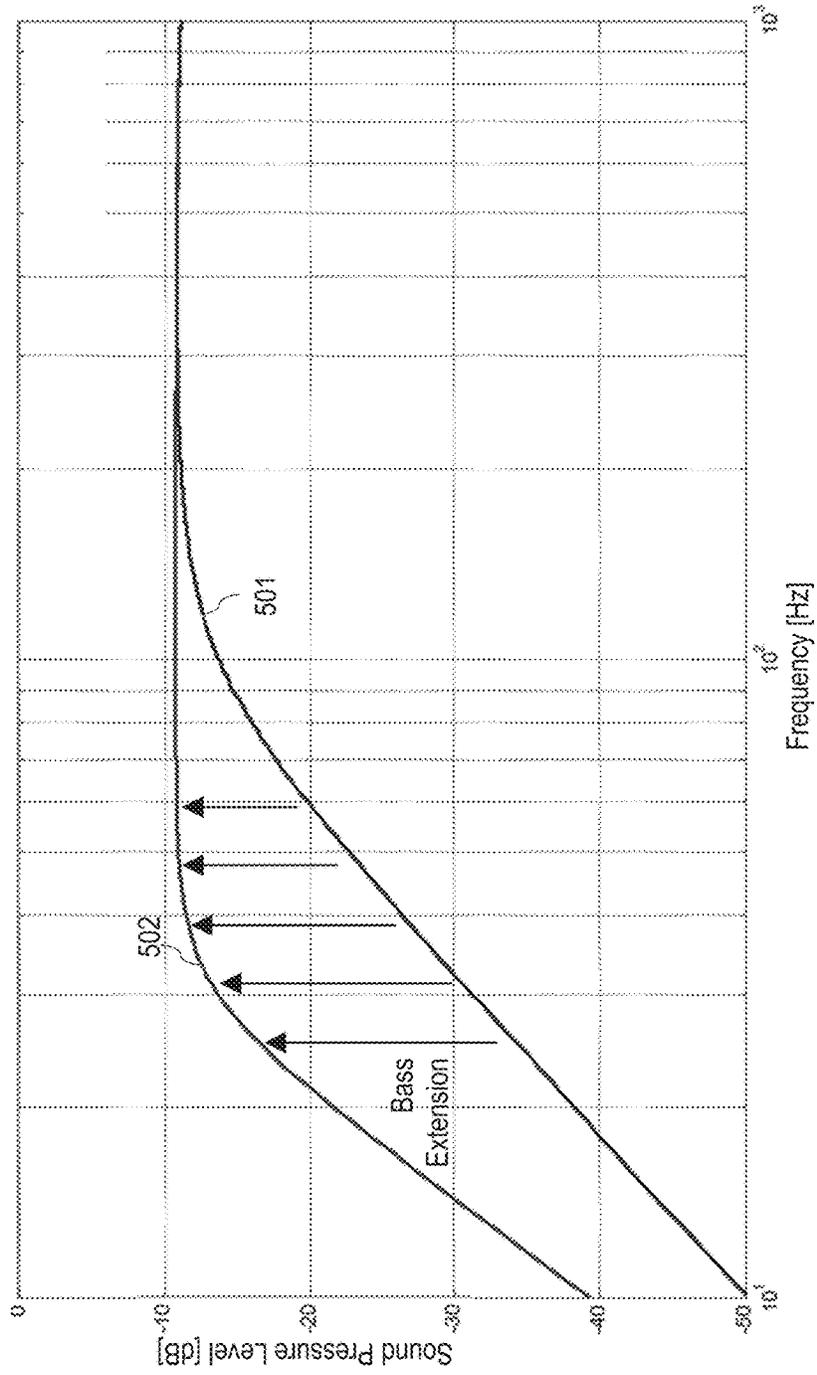
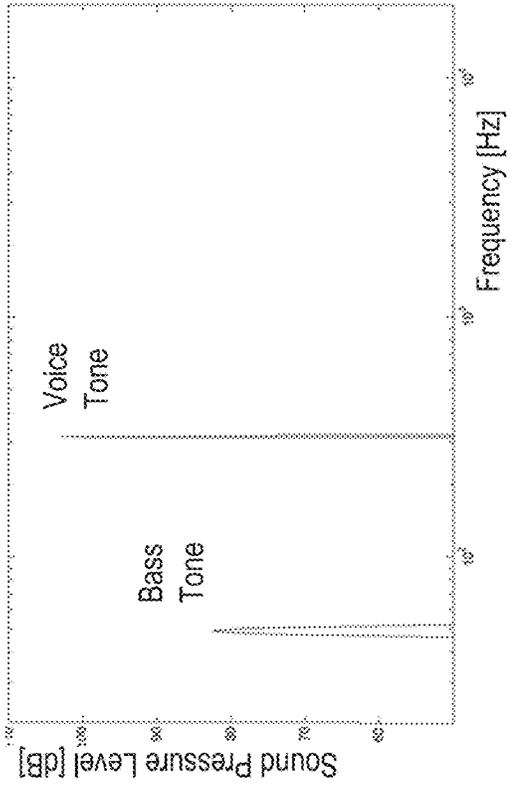


FIG. 11

520



510

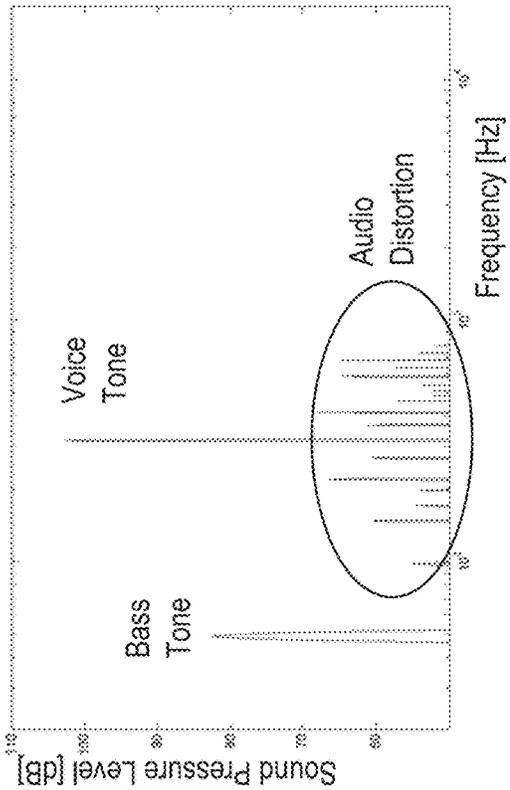


FIG. 12B

FIG. 12A

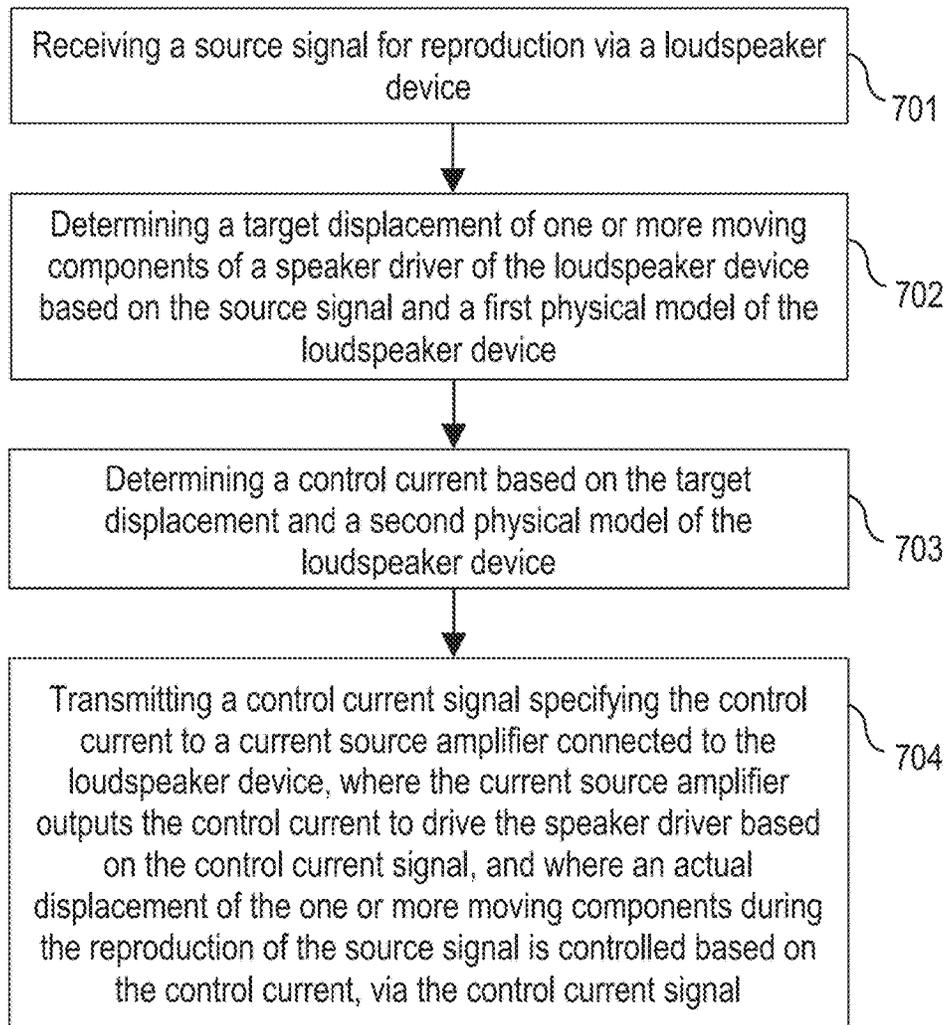
**700**

FIG. 13

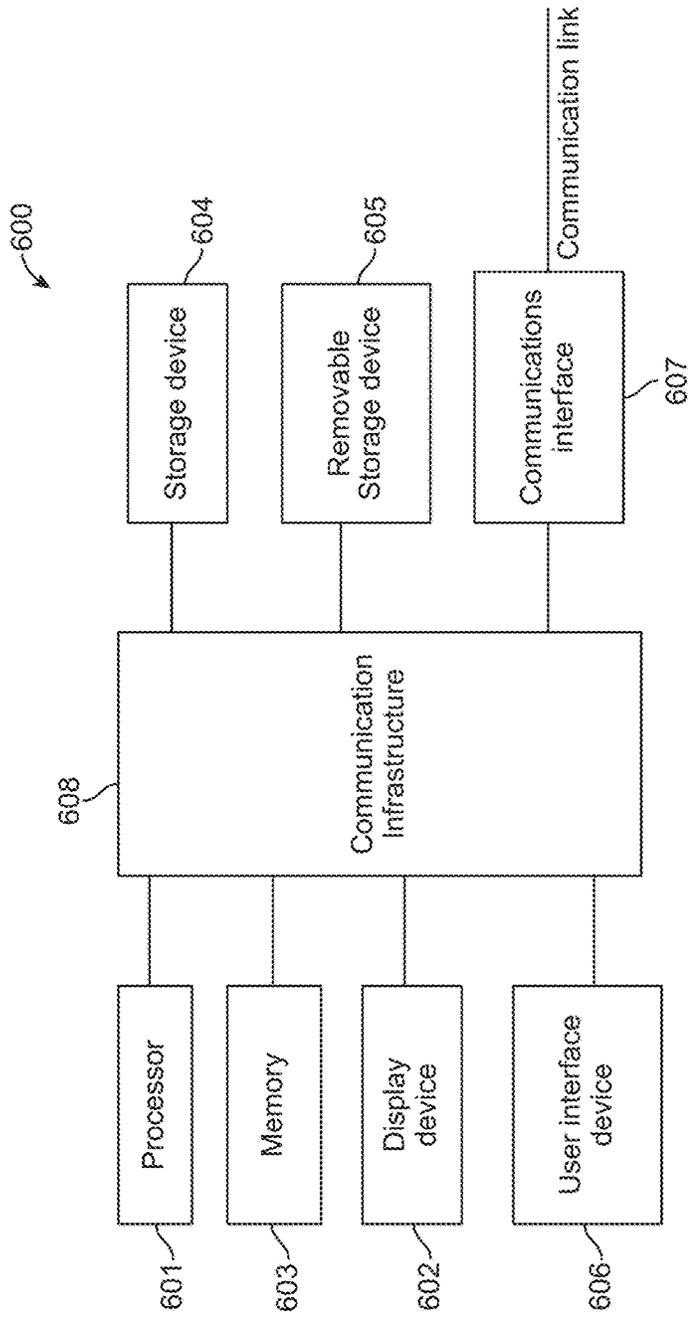


FIG. 14

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# NONLINEAR CONTROL OF LOUDSPEAKER SYSTEMS WITH CURRENT SOURCE AMPLIFIER

TECHNICAL FIELD

One or more embodiments relate generally to loudspeakers, and in particular, a method and system for nonlinear control of loudspeaker systems with current source amplifier.

BACKGROUND

A loudspeaker produces sound when connected to an integrated amplifier, a television (TV) set, a radio, a music player, an electronic sound producing device (e.g., a smartphone, a computer), a video player, etc.

SUMMARY

One embodiment provides a system for nonlinear control of a loudspeaker. The system comprises a current source amplifier connected to the loudspeaker, and a controller connected to the current source amplifier. The controller is configured to determine a target displacement of a diaphragm of a speaker driver of the loudspeaker based on a source signal for reproduction via the loudspeaker, determine a control current based on the target displacement of the diaphragm and a first physical model of the loudspeaker, and transmit a control current signal specifying the control current to the current source amplifier. The current source amplifier outputs the control current to drive the speaker driver based on the control current signal. An actual displacement of the diaphragm during the reproduction of the source signal is controlled based on the control current, via the control current signal.

Another embodiment provides a method for nonlinear control of a loudspeaker. The method comprises determining a target displacement of a diaphragm of a speaker driver of the loudspeaker based on a source signal for reproduction via the loudspeaker. The method further comprises determining a control current based on the target displacement of the diaphragm and a physical model of the loudspeaker, and transmitting a control current signal specifying the control current to a current source amplifier connected to the loudspeaker. The current source amplifier outputs the control current to drive the speaker driver based on the control current signal. An actual displacement of the diaphragm during the reproduction of the source signal is controlled based on the control current, via the control current signal.

One embodiment provides a loudspeaker device comprising a speaker driver including a diaphragm, a current source amplifier connected to the speaker driver, and a controller connected to the current source amplifier. The controller is configured to determine a target displacement of a diaphragm of the speaker driver based on a source signal for reproduction via the loudspeaker device, determine a control current based on the target displacement of the diaphragm and a physical model of the loudspeaker device, and transmit a control current signal specifying the control current to the current source amplifier. The current source amplifier outputs the control current to drive the speaker driver based on the control current signal. An actual displacement of the diaphragm during the reproduction of the source signal is controlled based on the control current, via the control current signal.

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These and other features, aspects and advantages of the one or more embodiments will become understood with reference to the following description, appended claims, and accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a cross section of an example speaker driver;

FIG. 2 illustrates an example loudspeaker device driven by a voltage source amplifier;

FIG. 3 illustrates an example electroacoustic model for the loudspeaker device in FIG. 2;

FIG. 4 is an example graph illustrating nonlinear characteristics of different large-signal loudspeaker parameters for the loudspeaker device in FIG. 2;

FIG. 5A illustrates an example linear system representing a linear state-space model of the loudspeaker device in FIG. 2;

FIG. 5B illustrates an example nonlinear system representing a nonlinear state-space physical model of the loudspeaker device in FIG. 2;

FIG. 6 illustrates an example loudspeaker control system for nonlinear control of a loudspeaker device with a current source amplifier, in accordance with an embodiment;

FIG. 7 illustrates an example electroacoustic model for the loudspeaker device in FIG. 6, in accordance with an embodiment;

FIG. 8A illustrates an example linear system representing a linear state-space model of the loudspeaker device in FIG. 6, in accordance with an embodiment;

FIG. 8B illustrates an example nonlinear system representing a nonlinear state-space model of the loudspeaker device in FIG. 6, in accordance with an embodiment;

FIG. 9 illustrates an example controller for the loudspeaker device in FIG. 6, in accordance with an embodiment;

FIG. 10 illustrates another example controller for the loudspeaker device in FIG. 6, in accordance with an embodiment;

FIG. 11 is an example graph comparing frequency responses of a loudspeaker device with nonlinear control active and the same loudspeaker device without nonlinear control active, in accordance with an embodiment;

FIG. 12A is an example graph illustrating a frequency spectrum of a loudspeaker device without nonlinear control for correction of audio distortion (i.e., without anti-distortion);

FIG. 12B is an example graph illustrating a frequency spectrum of a loudspeaker device with nonlinear control for correction of audio distortion (i.e., with anti-distortion), in accordance with an embodiment;

FIG. 13 is an example flowchart of a process for implementing nonlinear control of a loudspeaker device with a current source amplifier, in accordance with an embodiment; and

FIG. 14 is a high-level block diagram showing an information processing system comprising a computer system useful for implementing various disclosed embodiments.

DETAILED DESCRIPTION

The following description is made for the purpose of illustrating the general principles of one or more embodiments and is not meant to limit the inventive concepts claimed herein. Further, particular features described herein can be used in combination with other described features in

each of the various possible combinations and permutations. Unless otherwise specifically defined herein, all terms are to be given their broadest possible interpretation including meanings implied from the specification as well as meanings understood by those skilled in the art and/or as defined in dictionaries, treatises, etc.

One or more embodiments relate generally to loudspeakers, and in particular, a method and system for nonlinear control of loudspeaker systems with current source amplifier. One embodiment provides a system for nonlinear control of a loudspeaker. The system comprises a current source amplifier connected to the loudspeaker, and a controller connected to the current source amplifier. The controller is configured to determine a target displacement of a diaphragm of a speaker driver of the loudspeaker based on a source signal for reproduction via the loudspeaker, determine a control current based on the target displacement of the diaphragm and a first physical model of the loudspeaker, and transmit a control current signal specifying the control current to the current source amplifier. The current source amplifier outputs the control current to drive the speaker driver based on the control current signal. An actual displacement of the diaphragm during the reproduction of the source signal is controlled based on the control current, via the control current signal.

Another embodiment provides a method for nonlinear control of a loudspeaker. The method comprises determining a target displacement of a diaphragm of a speaker driver of the loudspeaker based on a source signal for reproduction via the loudspeaker. The method further comprises determining a control current based on the target displacement of the diaphragm and a physical model of the loudspeaker, and transmitting a control current signal specifying the control current to a current source amplifier connected to the loudspeaker. The current source amplifier outputs the control current to drive the speaker driver based on the control current signal. An actual displacement of the diaphragm during the reproduction of the source signal is controlled based on the control current, via the control current signal.

One embodiment provides a loudspeaker device comprising a speaker driver including a diaphragm, a current source amplifier connected to the speaker driver, and a controller connected to the current source amplifier. The controller is configured to determine a target displacement of a diaphragm of the speaker driver based on a source signal for reproduction via the loudspeaker device, determine a control current based on the target displacement of the diaphragm and a physical model of the loudspeaker device, and transmit a control current signal specifying the control current to the current source amplifier. The current source amplifier outputs the control current to drive the speaker driver based on the control current signal. An actual displacement of the diaphragm during the reproduction of the source signal is controlled based on the control current, via the control current signal.

For expository purposes, the terms “loudspeaker”, “loudspeaker device” and “loudspeaker system” may be used interchangeably in this specification.

For expository purposes, the terms “displacement” and “excursion” may be used interchangeably in this specification.

A conventional loudspeaker is nonlinear by design and produces harmonics, intermodulation components, and modulation noise. Nonlinear audio distortion (i.e., audible distortion) impairs sound quality of audio produced by the loudspeaker (e.g., audio quality and speech intelligibility). In recent times, industrial design constraints often require

loudspeaker systems to be smaller-sized for portability and compactness. Such design constraints, however, trade size and portability for sound quality, resulting in increased audio distortion. As such, an anti-distortion system for reducing/removing audio distortion is needed, in particular for obtaining a more pronounced/bigger bass sound from smaller-sized loudspeaker systems.

A loudspeaker device includes at least one speaker driver for reproducing sound. FIG. 1 illustrates a cross section of an example speaker driver 55. The speaker driver 55 comprises one or more moving components, such as a diaphragm 56 (e.g., a cone-shaped diaphragm), a driver voice coil 57, a former 64, and a protective cap 60 (e.g., a dome-shaped dust cap). The speaker driver 55 further comprises one or more of the following components: (1) a surround roll 58 (e.g., suspension roll), (2) a basket 59, (3) a top plate 61, (4) a magnet 62, (5) a bottom plate 63, (6) a pole piece 66, and (7) a spider 67.

Conventionally, a loudspeaker device is driven by a voltage source amplifier. FIG. 2 illustrates an example loudspeaker device 40 driven by a voltage source amplifier 71. The loudspeaker device 40 includes a speaker driver 45 for reproducing sound. The loudspeaker device 40 may be any type of loudspeaker device such as, but not limited to, a sealed-box loudspeaker, a vented-box loudspeaker, a passive radiator loudspeaker, a loudspeaker array, etc. The speaker driver 45 may be any type of speaker driver such as, but not limited to, a forward-facing speaker driver, an upward-facing speaker driver, a downward-facing speaker driver, etc. The speaker driver 55 in FIG. 1 is an example implementation of the speaker driver 45. The speaker driver 45 comprises one or more moving components, such as a diaphragm 56 (FIG. 1) and a driver voice coil 57 (FIG. 1).

The voltage source amplifier 71 is connected to the loudspeaker device 40. An input source 30 provides the voltage source amplifier 71 a source signal (e.g., an input audio signal) for audio reproduction. Let  $h^*$  generally denote an input voltage of the source signal. The voltage source amplifier 71 is configured to apply a voltage  $u$  to the speaker driver 45, amplifying the source signal for reproduction via the loudspeaker device 40. The speaker driver 45 is driven by applied voltage  $u$  from the voltage source amplifier 71. The loudspeaker device 40 produces a sound wave with an actual sound pressure  $p$ .

FIG. 3 illustrates an example electroacoustic model 70 for a loudspeaker device 40 (FIG. 2) driven by a voltage source amplifier 71. One or more loudspeaker parameters (i.e., loudspeaker characteristics) for the loudspeaker device 40 may be classified into one of the following domains: an electrical domain or a mechanical domain. In the electrical domain, examples of different loudspeaker parameters include, but are not limited to, the following: (1) an applied voltage  $u$  from the voltage source amplifier 71 for driving a speaker driver 45 of the loudspeaker device 40, (2) an electrical resistance  $R_e$  of a driver voice coil 57 of the speaker driver 45, (3) a current  $i$  flowing through the driver voice coil 57 as a result of the applied voltage  $u$ , (4) an inductance  $L_e$  of the driver voice coil 57, and (5) a back-electromagnetic force (back-EMF)  $Bl \cdot \dot{x}$  resulting from the motion of the driver voice coil 57 in the magnetic field of the motor structure (i.e., driver voice coil 57, top plate 61, magnet 62, bottom plate 63, and pole piece 66) of the speaker driver 45, wherein the back-EMF  $Bl \cdot \dot{x}$  represents a product of a force factor  $Bl$  of the motor structure and a velocity  $\dot{x}$  of one or more moving components of the speaker driver 45 (e.g., a diaphragm 56, the driver voice coil 57, and/or the former 64).

## 5

In the mechanical domain, examples of different loudspeaker parameters include, but are not limited to, the following: (1) the velocity  $\dot{x}$  of the one or more moving components of the speaker driver **45**, (2) a mechanical mass  $M_{ms}$  of the one or more moving components (i.e., moving mass) and air load, (3) a mechanical resistance  $R_{ms}$  representing the mechanical losses of the speaker driver **45**, (4) a stiffness factor  $K_{ms}$  of the suspension (i.e., surround roll **58**, spider **67**, plus air load) of the speaker driver **45**, and (5) a mechanical force  $BI \cdot i$  applied on the one or more moving components, wherein the mechanical force  $BI \cdot i$  represents a product of the force factor  $BI$  of the motor structure and the current  $i$  flowing through the driver voice coil **57**.

The mechanical force  $BI \cdot i$  is proportional to the current  $i$  flowing through the driver voice coil **57**, not the applied voltage  $u$  from the voltage source amplifier **71**. The current  $i$  flowing through the driver voice coil **57** is affected by nonlinear impedances  $R_e$  and  $L_e$ .

FIG. 4 is an example graph **150** illustrating nonlinear characteristics of different large-signal loudspeaker parameters for a loudspeaker device **40** (FIG. 2). A horizontal axis of the graph **150** represents displacement of one or more moving components (e.g., a diaphragm **56** and/or a driver voice-coil **57**) of a speaker driver **45** of the loudspeaker device **40** in m. The graph **150** comprises each of the following: (1) a first curve **151** representing changes in force factor  $BI$  in Newton per Ampere (N/A), (2) a second curve **152** representing changes in stiffness factor  $K_{ms}$  in Newton per m (N/m), and (3) a third curve **153** representing changes in inductance  $L_e$  in millihenry (mH). As shown in FIG. 4, the large-signal loudspeaker parameters change with displacement of the one or more moving components.

The state of a loudspeaker device **40** at each instant may be described using each of the following: (1) a displacement  $x$  of the one or more moving components of the speaker driver **45**, (2) a velocity  $\dot{x}$  of the one or more moving components of the speaker driver **45**, and (3) a current  $i$  flowing through the driver voice coil **57**. Let  $X_1(t)$  generally denote a vector representing a state ("state vector representation") of the loudspeaker device **40** at a sampling time  $t$ . The state vector representation  $X_1(t)$  may be defined in accordance with equation (1) provided below:

$$X_1(t) = [x, \dot{x}, i]^T \quad (1).$$

For expository purposes, the terms  $X_1(t)$  and  $X_1$  are used interchangeably in this specification.

As described in detail later herein below, an estimated displacement  $x$  of the one or more moving components at a sampling time  $t$  may be determined using a physical model of the loudspeaker device **40**, such as a linear model (e.g., a linear state-space model as shown in FIG. 5A) or a nonlinear model (e.g., a nonlinear state-space model as shown in FIG. 5B). The physical model may be based on one or more loudspeaker parameters for the loudspeaker device **40**.

FIG. 5A illustrates an example linear system **400** representing a linear state-space model of the loudspeaker device **40**. The linear system **400** may be utilized to determine an estimated displacement  $x$  of one or more moving components (e.g., a diaphragm **56** and/or a driver voice coil **57**) of the speaker driver **45** based on a state vector representation  $X_1$  of the loudspeaker device **40** and an input voltage  $u$  of a source signal for reproduction via the loudspeaker device **40**.

Let  $\dot{X}_1$  generally denote a time derivative (i.e., rate of change) of the state vector representation  $X_1$  of the loudspeaker device **40** ("state vector rate of change"). The state

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vector rate of change  $\dot{X}_1$  may be defined in accordance with a differential equation (2) provided below:

$$\dot{X}_1 = A_1 X_1 + B_1 u \quad (2).$$

Let  $A_1$ ,  $B_1$ , and  $C_1$  denote constant parameter matrices. The constant parameter matrices  $A_1$ ,  $B_1$ , and  $C_1$  may be represented in accordance with equations (3)-(5) provided below:

$$A_1 = \begin{bmatrix} 0 & 1 & 0 \\ -K_{ms}/M_{ms} & -R_{ms}/M_{ms} & BI/M_{ms} \\ 0 & -BI/L_e & -R_e/L_e \end{bmatrix}, \quad (3)$$

$$B_1 = \begin{bmatrix} 0 \\ 0 \\ 1/L_e \end{bmatrix}, \text{ and} \quad (4)$$

$$C_1 = [1 \ 0 \ 0]. \quad (5)$$

An estimated displacement  $x$  of the one or more moving components of the speaker driver **45** may be computed in accordance with equation (6) provided below:

$$x = C_1 X_1 \quad (6).$$

Determining an estimated displacement  $x$  of the one or more moving components utilizing the linear system **400** involves performing a set of computations that are based on equations (2)-(6) provided above. The linear system **400** may utilize one or more of the following components to perform the set of computations: (1) a first multiplication unit **401** configured to determine a product term  $A_1 X_1$  by multiplying the constant parameter matrix  $A_1$  with the state vector representation  $X_1$ , (2) a second multiplication unit **402** configured to determine a product term  $B_1 u$  by multiplying the constant parameter matrix  $B_1$  with the input voltage  $u$ , (3) an addition unit **403** configured to determine the state vector rate of change  $\dot{X}_1$  by adding the product terms  $A_1 X_1$  and  $B_1 u$  in accordance with equation (2) provided above, (4) an integration unit **404** configured to determine the state vector representation  $X_1$  by integrating the state vector rate of change  $\dot{X}_1$  in the time domain, and (5) a third multiplication unit **405** configured to determine the estimated displacement  $x$  by multiplying the constant parameter matrix  $C_1$  with the state vector representation  $X_1$  in accordance with equation (6) provided above.

The system representation **400** in FIG. 5A is a linear system that receives an input voltage  $u$  as an input and provides an estimated displacement  $x$  as an output.

FIG. 5B illustrates an example nonlinear system **450** representing a nonlinear state-space physical model of the loudspeaker device **40**. The nonlinear system **450** may be utilized to determine an estimated displacement  $x$  of one or more moving components (e.g., a diaphragm **56** and/or a driver voice coil **57**) of the speaker driver **45** based on a state vector representation  $X_1$  of the loudspeaker device **40** and an input voltage  $u$  of a source signal for reproduction via the loudspeaker device **40**.

Let  $g_1(X_1, u)$  and  $f_1(X_1)$  generally denote nonlinear functions that are based on the state vector representation  $X_1$  of the loudspeaker device **40** and one or more large signal loudspeaker parameters for the loudspeaker device **40**. The nonlinear functions  $g_1(X_1, u)$  and  $f_1(X_1)$  may be represented in accordance with equations (7)-(8) provided below:

$$g_1(X_1, u) = [0 \ 0 \ u/L_e(x)]^T, \text{ and} \quad (7)$$

$$f_1(X_1) = \begin{bmatrix} \dot{x} \\ (1/M_{ms})(-K_{ms}(x)x - R_{ms}(\dot{x}) \cdot \dot{x} + B_l(x) \cdot i + (\dot{t}^2/2)(dL_e/dx)) \\ (1/L_e(x))(-B_l(x) \cdot \dot{x} - R_e(T) \cdot i - (dL_e/dx)\dot{x} \cdot i) \end{bmatrix}. \quad (8)$$

Let  $C_1$  generally denote a constant parameter matrix. The constant parameter matrix  $C_1$  may be represented in accordance with equation (9) provided below:

$$C_1 = [1 \ 0 \ 0] \quad (9).$$

Let  $\dot{X}_1$  generally denote a time derivative (i.e., rate of change) of the state vector representation  $X_1$  of the loudspeaker device **40** (“state vector rate of change”). The state vector rate of change  $\dot{X}_1$  may be defined in accordance with a differential equation (10) provided below:

$$\dot{X}_1 = g_1(X_1, u) + f_1(X_1) \quad (10).$$

An estimated displacement  $x$  of the one or more moving components of the speaker driver **45** may be computed in accordance with equation (11) provided below:

$$x = C_1 X_1 \quad (11).$$

Determining an estimated displacement  $x$  of the one or more moving components utilizing the nonlinear system **450** involves performing a set of computations that are based on equations (7)-(11) provided above. The nonlinear system **450** may utilize one or more of the following components to perform the set of computations: (1) a first computation unit **451** configured to compute the nonlinear function  $f_1(X_1)$  in accordance with equation (8) provided above, (2) a second computation unit **452** configured to compute the nonlinear function  $g_1(X_1, u)$  in accordance with equation (7) provided above, (3) an addition unit **453** configured to determine the state vector rate of change  $\dot{X}_1$  by adding the nonlinear functions  $g_1(X_1, u)$  and  $f_1(X_1)$  in accordance with equation (10) provided above, (4) an integration unit **454** configured to determine the state vector representation  $X_1$  by integrating the state vector rate of change  $\dot{X}_1$  in the time-domain, and (5) a multiplication unit **455** configured to determine the estimated displacement  $x$  by multiplying the constant parameter matrix  $C_1$  with the state vector representation  $X_1$  in accordance with equation (11) provided above.

The system representation **450** in FIG. 5B is a nonlinear system that receives an input voltage  $u$  as an input and provides an estimated displacement  $x$  as an output.

Compared to conventional loudspeakers, one or more embodiments provide a system for nonlinear control (“nonlinear control system”) of a loudspeaker device with a current source amplifier. The nonlinear control system is configured to improve sound quality of the loudspeaker device by reducing audio distortion. In one embodiment, the nonlinear control system provides correction of nonlinear audio distortion by pre-distorting current to a speaker driver of the loudspeaker device. The nonlinear control system provides improved performance in terms of reduced audio distortion, bass extension, displacement control, and loudspeaker protection.

The nonlinear control system is configured to increase or maximize bass output of the loudspeaker device by controlling motion of one or more moving components (e.g., a diaphragm and/or a driver voice coil) of the speaker driver. In one embodiment, the nonlinear control system enables linearization of the loudspeaker device by providing nonlinear control of motion of the one or more moving components. This allows for increased/maximum bass extension, thereby enhancing bass output of the loudspeaker device. By preventing excessive displacements of the one or

more moving components and overheating of the loudspeaker device, the nonlinear control system provides improved protection of the loudspeaker device.

FIG. 6 illustrates an example loudspeaker system **100**, in accordance with an embodiment. The loudspeaker system **100** is an example nonlinear control system for a loudspeaker device with a current source amplifier. Specifically, the loudspeaker system **100** comprises a loudspeaker device **60** including a speaker driver **65** for reproducing sound. The loudspeaker device **60** may be any type of loudspeaker device such as, but not limited to, a sealed-box loudspeaker, a vented-box loudspeaker, a passive radiator loudspeaker, a loudspeaker array, etc. The speaker driver **65** may be any type of speaker driver such as, but not limited to, a forward-facing speaker driver, an upward-facing speaker driver, a downward-facing speaker driver, etc. The speaker driver **55** in FIG. 1 is an example implementation of the speaker driver **65**. The speaker driver **65** comprises one or more moving components, such as a diaphragm **56** (FIG. 1) and a driver voice coil **57** (FIG. 1).

The loudspeaker system **100** comprises a controller **110** configured to receive a source signal (e.g., an input audio signal) from an input source **10** for reproduction via the loudspeaker device **60**. In one embodiment, the controller **110** is configured to receive a source signal from different types of input sources **10**. Examples of different types of input sources **10** include, but are not limited to, a mobile electronic device (e.g., a smartphone, a laptop, a tablet, etc.), a content playback device (e.g., a television, a radio, a computer, a music player such as a CD player, a video player such as a DVD player, a turntable, etc.), or an audio receiver, etc.

Let  $p^*$  generally denote a target (i.e., desired) sound pressure for the loudspeaker device **60** to deliver during the reproduction of the source signal. As described in detail later herein, the controller **110** is configured to determine, based on a physical model of the loudspeaker device **60** and a target sound pressure  $p^*$  at a sampling time  $t$ , one or more of the following: (1) a target displacement (e.g., target cone displacement)  $x^*$  of the one or more moving components at the sampling time  $t$ , and (2) a target current  $i^*$  that produces the target displacement  $x^*$  at the sampling time  $t$ . For expository purposes, the terms “target current” and “control current” may be used interchangeably in this specification. The controller **110** is configured to generate and transmit a control current signal  $s$  specifying the target current  $i^*$  determined to a current source amplifier **81** of the loudspeaker system **100**. The control current signal  $s$  can be any type of signal such as, but not limited to, a current, a voltage, a digital signal, an analog signal, etc.

A physical model of the loudspeaker device **60** may be based on one or more loudspeaker parameters for the loudspeaker device **60**. In one embodiment, a physical model of the loudspeaker device **60** utilized by the controller **110** is a linear model (e.g., a linear state-space model as shown in FIG. 8A). In another embodiment, a physical model of the loudspeaker device **60** utilized by the controller **110** is a nonlinear model (e.g., a nonlinear state-space model as shown in FIG. 8B).

As shown in FIG. 6, the current source amplifier **81** is connected to the loudspeaker device **60** and the controller **110**. The current source amplifier **81** is a power amplifier configured to output (i.e., apply or produce), for each sampling time  $t$ , an actual current (i.e., applied current)  $i^*$  based on a control current signal  $s$  received from the controller **110**, wherein the control current signal  $s$  specifies a target current  $i^*$  determined by the controller **110** at the sampling time  $t$ . The control current signal  $s$  controls the current source amplifier **81**, directing the current source amplifier **81** to output an amount of current that is substan-

tially the same as the target current  $i^*$ . The speaker driver **65** is driven by the actual current  $i^*$  output by the current source amplifier **81**, thereby controlling an actual displacement of the one or more moving components during the reproduction of the source signal. Specifically, the loudspeaker system **100** controls cone displacement/motion of the one or more moving components by performing current correction based on the target current  $i^*$ , resulting in production of a target sound wave with a target sound pressure  $p^*$  at the sampling time  $t$ . The target current  $i^*$  limits an actual displacement (e.g., actual cone displacement) of the one or more moving components within a predetermined range of safe displacement.

The loudspeaker system **100** facilitates a higher level of audio reproduction, with improved sound quality, and additional control and protection of the loudspeaker device **60**.

As described in detail later herein, the controller **110** is configured to counter audio distortion during the reproduction of the source signal via the speaker driver **65** by calculating a target current  $i^*$  that is required to produce a target sound pressure  $p^*$  at each instant/sampling time  $t$  based on an instantaneous position of the one or more moving components, wherein an actual current output of the current source amplifier **81** is substantially equal to the target current  $i^*$ .

In one embodiment, the loudspeaker system **100** may be integrated in different types of electrodynamic transducers with a broad range of applications such as, but not limited to, the following: computers, televisions (TVs), smart devices (e.g., smart TVs, smart phones, etc.), soundbars, subwoofers, wireless and portable speakers, mobile phones, car speakers, etc.

Compared to conventional systems that utilize a voltage source amplifier (e.g., the loudspeaker device **40** driven by the voltage source amplifier **71** in FIG. 2), the loudspeaker system **100** implements nonlinear control of the loudspeaker device **60** with the current source amplifier. As described in detail later herein, the loudspeaker system **100** with current source amplifier is a simplified nonlinear control system with reduced requirements and costs. For example, the loudspeaker system **100** may require about half of digital signal processing (DSP) requirements of similar loudspeaker systems with voltage source amplifier, and has lower costs.

FIG. 7 illustrates an example electroacoustic model **80** for the loudspeaker device **60**, in accordance with an embodiment. One or more loudspeaker parameters (i.e., loudspeaker characteristics) for the loudspeaker device **60** may be classified into one of the following domains: an electrical domain or a mechanical domain. In the electrical domain, examples of different loudspeaker parameters include, but are not limited to, the following: (1) an actual current  $i^*$  output by the current source amplifier **81** for driving a speaker driver **65** of the loudspeaker device **60**, (2) an electrical resistance  $R_e(T)$  of a driver voice coil **57** of the speaker driver **65**, (3) an inductance  $L_e(x)$  of the driver voice coil **57**, and (4) a back-EMF  $Bl(x) \cdot \dot{x}$  resulting from the motion of the driver voice coil **57** in the magnetic field of the motor structure (i.e., driver voice coil **57**, top plate **61**, magnet **62**, bottom plate **63**, and pole piece **66**) of the speaker driver **65**, wherein the back-EMF  $Bl \cdot \dot{x}$  represents a product of a force factor  $Bl$  of the motor structure and a velocity  $\dot{x}$  of one or more moving components of the speaker driver **65** (e.g., a diaphragm **56**, the driver voice coil **57**, and/or the former **64**).

In the mechanical domain, examples of different loudspeaker parameters include, but are not limited to, the

following: (1) the velocity  $\dot{x}$  of the one or more moving components of the speaker driver **65**, (2) a mechanical mass  $M_{ms}$  of the one or more moving components (i.e., moving mass) and air load, (3) a resistance  $R_{ms}(\dot{x})$  representing mechanical losses of the speaker driver **65**, (4) a stiffness factor  $K_{ms}(x)$  of the suspension (i.e., surround roll **58**, spider **67**, plus air load) of the speaker driver **65**, and (5) a mechanical force  $Bl(x) \cdot i^*$  applied on the one or more moving components, wherein the mechanical force  $Bl(x) \cdot i^*$  represents a product of the force factor  $Bl(x)$  of the driver voice coil **57** and the actual current  $i^*$  output by the current source amplifier **81**.

Unlike a loudspeaker device driven by a voltage source amplifier (e.g., the loudspeaker device **40** in FIG. 2), nonlinear impedances  $R_e(T)$  and  $L_e(x)$  have no effect on the mechanical force  $Bl(x) \cdot i^*$  applied on the one or more moving components of the speaker driver **65** because the actual current  $i^*$  output by the current source amplifier **81** flows independent of the nonlinear impedances  $R_e(T)$  and  $L_e(x)$ . As the actual current  $i^*$  output by the current source amplifier **81** flows independent of nonlinear impedances, the controller **110** of the loudspeaker system **100** need not factor in these nonlinear impedances when performing computations, thereby simplifying the computations performed. As a result of the simplified computations, the loudspeaker system **100** may require about half of DSP requirements of conventional systems, and has lower costs.

A state of the loudspeaker device **60** at each instant may be described using each of the following: (1) a target displacement  $x$  of the one or more moving components of the speaker driver **65**, and (2) a velocity  $\dot{x}$  of the one or more moving components of the speaker driver **65**. Let  $X_2(t)$  generally denote a vector representing a state ("state vector representation") of the loudspeaker device **60** at a sampling time  $t$ . In one embodiment, the state vector representation  $X_2(t)$  may be defined in accordance with equation (12) provided below:

$$X_2(t) = [x, \dot{x}]^T \quad (12).$$

For expository purposes, the terms  $X_2(t)$  and  $X_2$  are used interchangeably in this specification.

FIG. 8A illustrates an example linear system **410** representing a linear state-space model of the loudspeaker device **60**, in accordance with an embodiment. The linear system **410** may be utilized to determine an estimated displacement  $x$  of one or more moving components (e.g., a diaphragm **56** and/or a driver voice coil **57**) of the speaker driver **65** based on a state vector representation  $X_2$  of the loudspeaker device **60** and a current  $i^*$  output by the current source amplifier **81** for driving the speaker driver **65**.

Let  $A_2$ ,  $B_2$ , and  $C_2$  generally denote constant parameter matrices. In one embodiment, the constant parameter matrices  $A_2$ ,  $B_2$ , and  $C_2$  may be represented in accordance with equations (13)-(15) provided below:

$$A_2 = \begin{bmatrix} 0 & 1 \\ -K_{ms}/M_{ms} & -R_{ms}/M_{ms} \end{bmatrix}, \quad (13)$$

$$B_2 = \begin{bmatrix} 0 \\ Bl/M_{ms} \end{bmatrix}, \text{ and} \quad (14)$$

$$C_2 = [1 \ 0]. \quad (15)$$

Let  $\dot{X}_2$  generally denote a time derivative (i.e., rate of change) of the state vector representation  $X_2$  of the loudspeaker device **60** ("state vector rate of change"). In one

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embodiment, the state vector rate of change  $\dot{X}_2$  may be defined in accordance with a differential equation (16) provided below:

$$\dot{X}_2 = A_2 X_2 + B_2 i^* \tag{16}$$

In one embodiment, an estimated displacement  $x$  of the one or more moving components may be computed in accordance with equation (17) provided below:

$$x = C_2 X_2 \tag{17}$$

In one embodiment, the controller **110** of the loudspeaker system **100** is configured to recursively determine an estimated displacement  $x$  of the one or more moving components utilizing the linear system **410**. Recursively determining an estimated displacement  $x$  of the one or more moving components utilizing the linear system **410** involves performing a recursive set of computations that are based on equations (13)-(17) provided above. In one example implementation, the controller **110** comprises one or more of the following components: (1) a first multiplication unit **411** configured to determine a product term  $A_2 X_2$  by multiplying the constant parameter matrix  $A_2$  with the state vector representation  $X_2$ , (2) a second multiplication unit **412** configured to determine a product term  $B_2 i^*$  by multiplying the constant parameter matrix  $B_2$  with the current  $i^*$ , (3) an addition unit **413** configured to determine the state vector rate of change  $\dot{X}_2$  by adding the product terms  $A_2 X_2$  and  $B_2 i^*$  in accordance with equation (16) provided above, (4) an integration unit **414** configured to determine the state vector representation  $X_2$  by integrating the state vector rate of change  $\dot{X}_2$  in the time-domain, and (5) a third multiplication unit **415** configured to determine an estimated displacement  $x$  by multiplying the constant parameter matrix  $C_2$  with the state vector representation  $X_2$  in accordance with equation (17) provided above.

As shown in FIG. 8A, the system **410** is a linear system that receives a current  $i^*$  as an input and provides an estimated displacement  $x$  as an output. Compared to the linear system **400** in FIG. 5A, utilizing the linear system **410** provides a reduction of system order with simplification of system transfer function. As the current  $i^*$  flows independent of nonlinear impedances  $R_e(T)$  and  $L_e(x)$  (i.e., no  $R_e(T)$  and  $L_e(x)$  dependence), the current source amplifier **81** provides an output (i.e.,  $i^*$ ) with high impedance and the system transfer function is unaffected by changes in the nonlinear impedances, thereby removing the need to optimize such nonlinear impedances. Therefore, utilizing the linear system **410** simplifies the nonlinear control of the loudspeaker device **60** and computations performed by the controller **110**. As a result, the loudspeaker system **100** may require about half of DSP requirements of conventional systems, and has lower costs.

FIG. 8B illustrates an example nonlinear system **460** representing a nonlinear state-space model of the loudspeaker device **60**, in accordance with an embodiment. The nonlinear system **460** may be utilized to determine an estimated displacement  $x$  of one or more moving components (e.g., a diaphragm **56** and/or a driver voice coil **57**) of the speaker driver **65** based on a state vector representation  $X_2$  of the loudspeaker device **60** and a current  $i^*$  output by the current source amplifier **81** for driving the speaker driver **65**.

Let  $g_2(X_2, i^*)$  and  $f_2(X_2)$  generally denote nonlinear functions that are based on the state vector representation  $X_2$  of the loudspeaker device **60** and one or more large signal loudspeaker parameters for the loudspeaker device **60**. In

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one embodiment, the nonlinear functions  $g_2(X_2, i^*)$  and  $f_2(X_2)$  are represented in accordance with equations (18)-(19) provided below:

$$g_2(X_2, i^*) = [0 \quad B(i^*) \cdot i^* / M_{ms}]^T, \text{ and} \tag{18}$$

$$f_2(X_2) = \begin{bmatrix} \dot{x} \\ (1/M_{ms})(-K_{ms}(x) \cdot x - R_{ms}(x) \cdot \dot{x}) \end{bmatrix} \tag{19}$$

Let  $C_2$  generally denote a constant parameter matrix. In one embodiment, the constant parameter matrix  $C_2$  may be represented in accordance with equation (20) provided below:

$$C_2 = [1 \quad 0] \tag{20}$$

Let  $\dot{X}_2$  generally denote a time derivative (i.e., rate of change) of the state vector representation  $X_2$  of the loudspeaker device **60** ("state vector rate of change"). In one embodiment, the state vector rate of change  $\dot{X}_2$  may be defined in accordance with a differential equation (21) provided below:

$$\dot{X}_2 = g_2(X_2, i^*) + f_2(X_2) \tag{21}$$

In one embodiment, an estimated displacement  $x$  of the one or more moving components of the speaker driver **65** may be computed in accordance with equation (22) provided below:

$$x = C_2 X_2 \tag{22}$$

In one embodiment, the controller **110** of the loudspeaker system **100** is configured to recursively determine an estimated displacement  $x$  of the one or more moving components of the speaker driver **65** utilizing the nonlinear system **460**. Recursively determining an estimated displacement  $x$  of the one or more moving components utilizing the nonlinear system **460** involves performing a recursive set of computations that are based on equations (18)-(22) provided above. The nonlinear system **460** may utilize one or more of the following components to perform the set of computations: (1) a first computation unit **461** configured to compute nonlinear function  $f_2(X_2)$  in accordance with equation (19) provided above, (2) a second computation unit **462** configured to compute nonlinear function  $g_2(X_2, i^*)$  in accordance with equation (18) provided above, (3) an addition unit **463** configured to determine the state vector rate of change  $\dot{X}_2$  by adding the nonlinear functions  $g_2(X_2, i^*)$  and  $f_2(X_2)$  in accordance with equation (21) provided above, (4) an integration unit **464** configured to determine the state vector representation  $X_2$  by integrating the state vector rate of change  $\dot{X}_2$  in the time-domain, and (5) a multiplication unit **465** configured to determine an estimated displacement  $x$  by multiplying the constant parameter matrix  $C_2$  with the state vector representation  $X_2$  in accordance with equation (22) provided above.

As shown in FIG. 8B, the system **460** is a nonlinear system that receives a current  $i^*$  as an input and provides an estimated displacement  $x$  as an output. Compared to the linear system **450** in FIG. 5B, utilizing the nonlinear system **460** provides a reduction of system order with simplification of system transfer function. As the current  $i^*$  flows independent of nonlinear impedances  $R_e(T)$  and  $L_e(x)$  (i.e., no  $R_e(T)$  and  $L_e(x)$  dependence), the current source amplifier **81** provides an output (i.e.,  $i^*$ ) with high impedance and the system transfer function is unaffected by changes in the nonlinear impedances, thereby removing the need to opti-

mize such nonlinear impedances. Therefore, utilizing the nonlinear system 460 simplifies the control of the loudspeaker device 60 and computations performed by the controller 110. As a result, the loudspeaker system 100 may require about half of DSP requirements of conventional systems, and has lower costs.

FIG. 9 illustrates an example controller 200 for the loudspeaker device 60, in accordance with an embodiment. In one embodiment, the controller 110 of the loudspeaker system 100 is the controller 200. In one embodiment, the controller 200 comprises a trajectory planning unit 210 configured to determine a target displacement (i.e., target cone displacement)  $x^*$  of one or more moving components (e.g., diaphragm 56 and/or driver voice coil 57) of the speaker driver 65 at each sampling time  $t$  based on a physical model of the loudspeaker device 60 and a target sound pressure  $p^*$  for the loudspeaker device 60 to deliver during reproduction of a source signal (e.g., input audio signal) at the sampling time  $t$ . In one embodiment, the loudspeaker system 100 is configured to determine the target sound pressure  $p^*$  from the source signal.

In one embodiment, the trajectory planning unit 210 utilizes a linear model (e.g., linear state-space model 400 in FIG. 5A or 410 in FIG. 8A) to determine a target displacement  $x^*$  of the one or more moving components, thereby implementing a trajectory planning that includes linear processing of the source signal. In another embodiment, the trajectory planning unit 210 utilizes a nonlinear model (e.g., nonlinear state-space model 450 in FIG. 5B or 460 in FIG. 8B) to determine a target displacement  $x^*$  of the one or more moving components.

In one embodiment, the controller 200 comprises a flatness based feedforward control unit 220 that implements feedforward control to determine a control current  $i^*$  for each sampling time  $t$ . Specifically, the flatness based feedforward control unit 220 is configured to determine, based on a target displacement  $x^*$  for a sampling time  $t$  received from the trajectory planning unit 210 and a physical model of the loudspeaker device 60 (e.g., a nonlinear model), a control current  $i^*$  to drive the speaker driver 65 to produce the target displacement  $x^*$ .

In one embodiment, the flatness based feedforward control unit 220 is configured to determine a control current  $i^*$  at a sampling time  $t$  based on a nonlinear model of the loudspeaker device 60. For example, in one embodiment, if the loudspeaker device 60 is a sealed-box loudspeaker, the flatness based feedforward control unit 220 may determine a control current  $i^*$  at a sampling time  $t$  in accordance with a single equation (23) provided below:

$$i^* = (K_{ms}(x^*) \cdot x^* + R_{ms}(\dot{x}^*) \cdot \dot{x}^* + M_{ms} \cdot \ddot{x}^*) / Bl(x^*) \quad (23),$$

wherein  $\dot{x}^*$  is a target velocity (e.g., target cone velocity) of the one or more moving components of the speaker driver 65,  $\ddot{x}^*$  is a target acceleration (e.g., target cone acceleration) of the one or more moving components,  $K_{ms}(x^*)$  is a stiffness factor of the suspension (i.e., surround roll 58, spider 67, plus air load) of the speaker driver 65 based on the target displacement  $x^*$ ,  $R_{ms}(\dot{x}^*)$  is a resistance representing the mechanical losses of the speaker driver 65 based on the target velocity  $\dot{x}^*$ , and  $Bl(x^*)$  is a force factor of a driver voice coil 57 of the speaker driver 65 based on the target displacement  $x^*$ . The flatness based feedforward control unit 220 is configured to generate and transmit a control current signal  $s$  specifying the control current  $i^*$  determined to the current source amplifier 81 of the loudspeaker system

100. The control current signal  $s$  can be any type of signal such as, but not limited to, a current, a voltage, a digital signal, an analog signal, etc.

The current source amplifier 81 of the loudspeaker system 100 is configured to output (i.e., apply or produce), for each sampling time  $t$ , an actual current (i.e., applied current)  $i^*$  based on a control current signal  $s$  received from the flatness based feedforward control unit 220, wherein the control current signal  $s$  specifies a control current  $i^*$  determined by the flatness based feedforward control unit 220 at the sampling time  $t$ . The control current signal  $s$  controls the current source amplifier 81, directing the current source amplifier 81 to output an amount of current that is substantially the same as the control current  $i^*$  at the sampling time  $t$ . The speaker driver 65 is driven by the actual current  $i^*$  from the current source amplifier 81, thereby controlling an actual displacement (i.e., actual cone displacement) of the one or more moving components of the speaker driver 65 during the reproduction of the source signal and resulting in production of a sound wave with an actual sound pressure  $p$ .

FIG. 10 illustrates an example controller 250 for the loudspeaker device 60, in accordance with an embodiment. In one embodiment, the controller 110 of the loudspeaker system 100 is the controller 250. In one embodiment, the controller 250 comprises a trajectory planning unit 260 configured to determine a target displacement (i.e., target cone displacement)  $x^*$  of one or more moving components (e.g., diaphragm 56 and/or driver voice coil 57) of the speaker driver 65 at each sampling time  $t$  based on a physical model of the loudspeaker device 60 and a target sound pressure  $p^*$  for the loudspeaker device 60 to deliver during reproduction of a source signal (e.g., input audio signal) at the sampling time  $t$ .

In one embodiment, the trajectory planning unit 260 utilizes a linear model (e.g., linear state-space model 400 in FIG. 5A or 410 in FIG. 8A) to determine a target displacement  $x^*$  of the one or more moving components, thereby implementing a trajectory planning that includes linear processing of the source signal. In another embodiment, the trajectory planning unit 260 utilizes a nonlinear model (e.g., nonlinear state-space model 450 on FIG. 5B or 460 in FIG. 8B) to determine a target displacement  $x^*$  of the one or more moving components.

In one embodiment, the controller 250 comprises a flatness based feedforward control unit 270 that implements feedforward control to determine a control current  $i^*$  for each sampling time  $t$ . Specifically, the flatness based feedforward control unit 270 is configured to determine, based on a target displacement  $x^*$  for a sampling time  $t$  received from the trajectory planning unit 260 and a physical model of the loudspeaker device 60, a control current  $i^*$  to drive the speaker driver 65 to produce the target displacement  $x^*$ .

In one embodiment, the flatness based feedforward control unit 270 is configured to determine a control current  $i^*$  at a sampling time  $t$  based on a nonlinear model of the loudspeaker device 60. For example, in one embodiment, if the loudspeaker device 60 is a sealed-box loudspeaker, the flatness based feedforward control unit 270 may determine a control current  $i^*$  at a sampling time  $t$  in accordance with the single equation (23) provided above. The flatness based feedforward control unit 270 is configured to generate and transmit a control current signal  $s$  specifying the control current  $i^*$  determined to the current source amplifier 81 of the loudspeaker system 100. The control current signal  $s$  can be any type of signal such as, but not limited to, a current, a voltage, a digital signal, an analog signal, etc.

The current source amplifier **81** of the loudspeaker system **100** is configured to output (i.e., apply or produce), for each sampling time  $t$ , an actual current (i.e., applied current)  $i^*$  based on a control current signal  $s$  received from the flatness based feedforward control unit **270**, wherein the control current signal  $s$  specifies a control current  $i^*$  determined by the flatness based feedforward control unit **270** at the sampling time  $t$ . The control current signal  $s$  controls the current source amplifier **81**, directing the current source amplifier **81** to output an amount of current that is substantially the same as the control current  $i^*$  at the sampling time  $t$ . The speaker driver **65** is driven by the actual current  $i^*$  from the current source amplifier **81**, thereby controlling an actual displacement (i.e., actual cone displacement) of the one or more moving components of the speaker driver **65** during the reproduction of the source signal and resulting in production of a sound wave with an actual sound pressure  $p$  at the sampling time  $t$ .

In one embodiment, the controller **250** is configured to monitor a voltage  $u$  measured at the terminals of the speaker driver **65** at each sampling time  $t$ . The controller **250** further comprises feedback control unit **280** configured to recalculate, based on the measured voltage  $u$  and the actual current  $i^*$  from the current source amplifier **81**, the one or more loudspeaker model parameters for the loudspeaker device **60**. Feedback control unit **280** provides updates of the one or more loudspeaker model parameters to the flatness based feedforward control unit **270**. The updates of the one or more loudspeaker model parameters may be used to minimize the inaccuracies. For example, the loudspeaker model parameters may be adjusted to compensate for variations originating from intrinsic and extrinsic variations, such as manufacturing tolerances, present operating conditions (e.g., temperature of driver voice coil **57**), environmental effects such as pressure and temperature, and aging of components and materials of the loudspeaker system **100**. Therefore, the loudspeaker system **100** may account for changes in components and materials that vary over time and environmental conditions, and counter detrimental effects of temperature (e.g., resistance variation of driver voice coil **57**), pressure, and aging.

In one embodiment, the controller **250** is configured to monitor a voltage  $u$  measured at the terminals of the speaker driver **65** at each sampling time  $t$ . The controller **250** further comprises feedback control unit **280** configured to recalculate, based on the measured voltage  $u$  and the control current signal  $s$  from the flatness based feedforward control unit **270**, the one or more loudspeaker model parameters for the loudspeaker device **60**. Feedback control unit **280** provides updates of the one or more loudspeaker model parameters to the flatness based feedforward control unit **270**. The updates of the one or more loudspeaker model parameters may be used to minimize the inaccuracies, providing improved control of the loudspeaker device, with reduced distortion.

Based on the loudspeaker model parameters generated, any resulting correction performed (e.g., current correction, or corrections to the one or more loudspeaker model parameters) may compensate for one or more inaccuracies (e.g., manufacturing dispersion, environmental conditions, component aging effects) associated with a physical model utilized by the controller **250** and/or audio drifting (e.g., resulting from heating of the loudspeaker device **60**). The correction performed may be used to minimize the inaccuracies.

For example, in one embodiment, the corrections to the one or more loudspeaker parameters may be used to provide a correction to the stiffness factor thereby improving the

accuracy of the loudspeaker system **100** and the quality of audio output produced by the loudspeaker device **60**.

The feedback control implemented by the flatness based feedforward control unit **270** may be based on various control methods such as, but not limited to, state feedback control, adaptive control (e.g., using an online system identification), Proportional-Integral-Derivative (PID) control, etc.

In another embodiment, if the speaker driver **65** has well known and stable characteristics, the flatness based feedforward control unit **270** need not factor into account any corrections, thereby removing the need for the feedback control unit **280** (e.g., similar to the controller **200** in FIG. **9**).

FIG. **11** is an example graph **500** comparing frequency responses of a loudspeaker device with nonlinear control active and the same loudspeaker device without nonlinear control active, in accordance with an embodiment. A horizontal axis of the graph **500** represents frequency in Hz. A vertical axis of the graph **500** represents sound pressure level in dB. The graph **500** comprises a first curve **501** representing frequency response of the loudspeaker device without nonlinear control active, and (2) a second curve **502** representing frequency response of the loudspeaker device with nonlinear control active (e.g., implemented using the loudspeaker system **100**).

If the loudspeaker device without nonlinear control active is integrated with one or more components of the loudspeaker system **100** (e.g., controller **200** or controller **250**), the loudspeaker system **100** can extend roll-off of the frequency response of the loudspeaker device in the low sound frequencies while maintaining low audio distortion and ensuring that displacement of one or more moving components (e.g., diaphragm and/or driver voice coil) of the loudspeaker device is within a safe range of operation. The loudspeaker system **100** provides a system that enables bass extension (i.e., deeper, louder bass) with lower audio distortion, as illustrated by the directional arrows shown in FIG. **11**.

FIG. **12A** is an example graph **510** illustrating a frequency spectrum of a loudspeaker device without nonlinear control for correction of audio distortion (i.e., without anti-distortion). A horizontal axis of the graph **510** represents frequency in Hz. A vertical axis of the graph **510** represents sound pressure level in dB. As shown in FIG. **12A**, effects of nonlinearities within the loudspeaker device may generate intermodulation products, thereby increasing audio distortion.

FIG. **12B** is an example graph **520** illustrating a frequency spectrum of a loudspeaker device with nonlinear control for correction of audio distortion (i.e., with anti-distortion), in accordance with an embodiment. The loudspeaker device may be integrated with one or more components of the loudspeaker system **100** (e.g., controller **200** or controller **250**). A horizontal axis of the graph **520** represents frequency in Hz. A vertical axis of the graph **520** represents sound pressure level in dB. Compared to the graph **510** in FIG. **12A**, effects of nonlinearities within the loudspeaker device are canceled out as shown in FIG. **12B**, thereby reducing intermodulation products and audio distortion.

FIG. **13** is an example flowchart of a process **700** for implementing nonlinear control of a loudspeaker device with a current source amplifier, in accordance with an embodiment. Process block **701** includes receiving a source signal for reproduction via a loudspeaker device (e.g., loudspeaker device **60**). Process block **702** includes determining a target displacement of one or more moving components

(e.g., diaphragm **56** and/or driver voice coil **57**) of a speaker driver of the loudspeaker device based on the source signal and a first physical model (e.g., linear state-space model **400** in FIG. **5A** or **410** in FIG. **8A**) of the loudspeaker device. Process block **703** includes determining a control current based on the target displacement and a second physical model of the loudspeaker device (e.g., nonlinear state-space model in FIG. **8B**). Process block **704** includes transmitting a control current signal specifying the control current to a current source amplifier connected to the loudspeaker device, where the current source amplifier outputs the control current to drive the speaker driver based on the control current signal, and where an actual displacement of the one or more moving components during the reproduction of the source signal is controlled based on the control current, via the control current signal.

In one embodiment, one or more components of the loudspeaker system **100**, such as the controller **200** or the controller **250**, are configured to perform process blocks **701-704**.

FIG. **14** is a high-level block diagram showing an information processing system comprising a computer system **600** useful for implementing various disclosed embodiments. The computer system **600** includes one or more processors **601**, and can further include an electronic display device **602** (for displaying video, graphics, text, and other data), a main memory **603** (e.g., random access memory (RAM)), storage device **604** (e.g., hard disk drive), removable storage device **605** (e.g., removable storage drive, removable memory module, a magnetic tape drive, optical disk drive, computer readable medium having stored therein computer software and/or data), user interface device **606** (e.g., keyboard, touch screen, keypad, pointing device), and a communication interface **607** (e.g., modem, a network interface (such as an Ethernet card), a communications port, or a PCMCIA slot and card).

The communication interface **607** allows software and data to be transferred between the computer system **600** and external devices. The nonlinear controller **600** further includes a communications infrastructure **608** (e.g., a communications bus, cross-over bar, or network) to which the aforementioned devices/modules **601** through **607** are connected.

Information transferred via the communications interface **607** may be in the form of signals such as electronic, electromagnetic, optical, or other signals capable of being received by communications interface **607**, via a communication link that carries signals and may be implemented using wire or cable, fiber optics, a phone line, a cellular phone link, a radio frequency (RF) link, and/or other communication channels. Computer program instructions representing the block diagrams and/or flowcharts herein may be loaded onto a computer, programmable data processing apparatus, or processing devices to cause a series of operations performed thereon to produce a computer implemented process. In one embodiment, processing instructions for process **700** (FIG. **13**) may be stored as program instructions on the memory **603**, storage device **604**, and/or the removable storage device **605** for execution by the processor **601**.

Embodiments have been described with reference to flowchart illustrations and/or block diagrams of methods, apparatus (systems), and computer program products. In some cases, each block of such illustrations/diagrams, or combinations thereof, can be implemented by computer program instructions. The computer program instructions when provided to a processor produce a machine, such that the instructions, which executed via the processor create

means for implementing the functions/operations specified in the flowchart and/or block diagram. Each block in the flowchart/block diagrams may represent a hardware and/or software module or logic. In alternative implementations, the functions noted in the blocks may occur out of the order noted in the figures, concurrently, etc.

The terms “computer program medium,” “computer usable medium,” “computer readable medium,” and “computer program product,” are used to generally refer to media such as main memory, secondary memory, removable storage drive, a hard disk installed in hard disk drive, and signals. These computer program products are means for providing software to the computer system. The computer readable medium allows the computer system to read data, instructions, messages or message packets, and other computer readable information from the computer readable medium. The computer readable medium, for example, may include non-volatile memory, such as a floppy disk, ROM, flash memory, disk drive memory, a CD-ROM, and other permanent storage. It is useful, for example, for transporting information, such as data and computer instructions, between computer systems. Computer program instructions may be stored in a computer readable medium that can direct a computer, other programmable data processing apparatuses, or other devices to function in a particular manner, such that the instructions stored in the computer readable medium produce an article of manufacture including instructions which implement the function/act specified in the flowchart and/or block diagram block(s).

As will be appreciated by one skilled in the art, aspects of the embodiments may be embodied as a system, method or computer program product. Accordingly, aspects of the embodiments may take the form of an entirely hardware embodiment, an entirely software embodiment (including firmware, resident software, micro-code, etc.) or an embodiment combining software and hardware aspects that may all generally be referred to herein as a “circuit,” “module,” or “system.” Furthermore, aspects of the embodiments may take the form of a computer program product embodied in one or more computer readable medium(s) having computer readable program code embodied thereon.

Any combination of one or more computer readable medium(s) may be utilized. The computer readable medium may be a computer readable storage medium (e.g., a non-transitory computer readable storage medium). A computer readable storage medium may be, for example, but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, or device, or any suitable combination of the foregoing. More specific examples (a non-exhaustive list) of the computer readable storage medium would include the following: an electrical connection having one or more wires, a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), an optical fiber, a portable compact disc read-only memory (CD-ROM), an optical storage device, a magnetic storage device, or any suitable combination of the foregoing. In the context of this document, a computer readable storage medium may be any tangible medium that can contain, or store a program for use by or in connection with an instruction execution system, apparatus, or device.

Computer program code for carrying out operations for aspects of one or more embodiments may be written in any combination of one or more programming languages, including an object oriented programming language such as Java, Smalltalk, C++, or the like, and conventional proce-

dural programming languages, such as the “C” programming language or similar programming languages. The program code may execute entirely on the user’s computer, partly on the user’s computer, as a stand-alone software package, partly on the user’s computer and partly on a remote computer or entirely on the remote computer or server. In the latter scenario, the remote computer may be connected to the user’s computer through any type of network, including a local area network (LAN) or a wide area network (WAN), or the connection may be made to an external computer (for example, through the Internet using an Internet Service Provider).

In some cases, aspects of one or more embodiments are described above with reference to flowchart illustrations and/or block diagrams of methods, apparatuses (systems), and computer program products. In some instances, it will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, can be implemented by computer program instructions. These computer program instructions may be provided to a special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the flowchart and/or block diagram block(s).

These computer program instructions may also be stored in a computer readable medium that can direct a computer, other programmable data processing apparatus, or other devices to function in a particular manner, such that the instructions stored in the computer readable medium produce an article of manufacture including instructions which implement the function/act specified in the flowchart and/or block diagram block(s).

The computer program instructions may also be loaded onto a computer, other programmable data processing apparatuses, or other devices to cause a series of operational steps to be performed on the computer, other programmable apparatuses, or other devices to produce a computer implemented process such that the instructions which execute on the computer or other programmable apparatuses provide processes for implementing the functions/acts specified in the flowchart and/or block diagram block(s).

The flowchart and block diagrams in the Figures illustrate the architecture, functionality, and operation of possible implementations of systems, methods, and computer program products according to various embodiments. In this regard, each block in the flowchart or block diagrams may represent a module, segment, or portion of instructions, which comprises one or more executable instructions for implementing the specified logical function(s). In some alternative implementations, the functions noted in the block may occur out of the order noted in the figures. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the block diagrams and/or flowchart illustration, and combinations of blocks in the block diagrams and/or flowchart illustration, can be implemented by special purpose hardware-based systems that perform the specified functions or acts or carry out combinations of special purpose hardware and computer instructions.

References in the claims to an element in the singular is not intended to mean “one and only” unless explicitly so stated, but rather “one or more.” All structural and functional

equivalents to the elements of the above-described exemplary embodiment that are currently known or later come to be known to those of ordinary skill in the art are intended to be encompassed by the present claims. No claim element herein is to be construed under the provisions of pre-AIA 35 U.S.C. section 112, sixth paragraph, unless the element is expressly recited using the phrase “means for” or “step for.”

The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms “a”, “an” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprises” and/or “comprising,” when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

The corresponding structures, materials, acts, and equivalents of all means or step plus function elements in the claims below are intended to include any structure, material, or act for performing the function in combination with other claimed elements as specifically claimed. The description of the embodiments has been presented for purposes of illustration and description, but is not intended to be exhaustive or limited to the embodiments in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the invention.

Though the embodiments have been described with reference to certain versions thereof; however, other versions are possible. Therefore, the spirit and scope of the appended claims should not be limited to the description of the preferred versions contained herein.

What is claimed is:

1. A system for nonlinear control of a loudspeaker, the system comprising:

a current source amplifier connected to the loudspeaker; and

a controller connected to the current source amplifier, wherein the controller is configured to:

determine a target displacement of a diaphragm of a speaker driver of the loudspeaker based on a source signal for reproduction via the loudspeaker;

determine a control current based on the target displacement of the diaphragm and a first physical model of the loudspeaker; and

transmit a control current signal specifying the control current to the current source amplifier, wherein the current source amplifier outputs the control current to drive the speaker driver based on the control current signal, and wherein an actual displacement of the diaphragm during the reproduction of the source signal is controlled based on the control current, via the control current signal.

2. The system of claim 1, wherein the first physical model is a nonlinear model.

3. The system of claim 1, wherein the controller is configured to determine the target displacement of the diaphragm based on a target sound pressure for the system to deliver during the reproduction of the source signal and a second physical model of the loudspeaker.

4. The system of claim 3, wherein the second physical model is a linear model.

5. The system of claim 3, wherein the second physical model is a nonlinear model.

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6. The system of claim 1, wherein the controller is further configured to:

monitor a voltage measured at terminals of the speaker driver during the reproduction of the source signal; and provide updates of one or more loudspeaker model parameters for the loudspeaker based on the measured voltage and the control current.

7. The system of claim 1, wherein the controller is further configured to:

monitor a voltage measured at terminals of the speaker driver during the reproduction of the source signal; and provide updates of one or more loudspeaker model parameters for the loudspeaker based on the measured voltage and the control current signal.

8. The system of claim 1, wherein the control current limits the actual displacement of the diaphragm within a predetermined range of safe displacement and increases bass output at low frequencies.

9. The system of claim 1, wherein the current source amplifier is configured to drive the speaker driver by amplifying the source signal based on the control current.

10. The system of claim 1, wherein a system transfer function of the system is independent of one or more of the following nonlinear impedances: an electrical resistance of a driver voice coil of the speaker driver, or an inductance of the driver voice coil.

11. The system of claim 1, wherein a mechanical force applied on the diaphragm is based on an actual current output by the current source amplifier, the actual current based on the control current, and the actual current independent of one or more of the following nonlinear impedances: an electrical resistance of a driver voice coil of the speaker driver, or an inductance of the driver voice coil.

12. A method for nonlinear control of a loudspeaker, the method comprising:

determining a target displacement of a diaphragm of a speaker driver of the loudspeaker based on a source signal for reproduction via the loudspeaker;

determining a control current based on the target displacement of the diaphragm and a physical model of the loudspeaker; and

transmitting a control current signal specifying the control current to a current source amplifier connected to the loudspeaker, wherein the current source amplifier outputs the control current to drive the speaker driver based on the control current signal, and wherein an actual displacement of the diaphragm during the reproduction of the source signal is controlled based on the control current, via the control current signal.

13. The method of claim 12, wherein the physical model is a nonlinear model.

14. The method of claim 12, wherein the method further comprises:

monitor a voltage measured at terminals of the speaker driver during the reproduction of the source signal; and

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provide updates of one or more loudspeaker model parameters for the loudspeaker based on the measured voltage and one of the control current or the control current signal.

15. The method of claim 12, wherein the control current limits the actual displacement of the diaphragm within a predetermined range of safe displacement and increases bass output at low frequencies.

16. The method of claim 12, wherein a mechanical force applied on the diaphragm is based on an actual current output by the current source amplifier, the actual current based on the control current, and the actual current independent of one or more of the following nonlinear impedances: an electrical resistance of a driver voice coil of the speaker driver, or an inductance of the driver voice coil.

17. A loudspeaker device comprising:  
a speaker driver including a diaphragm;  
a current source amplifier connected to the speaker driver; and

a controller connected to the current source amplifier, wherein the controller is configured to:

determine a target displacement of a diaphragm of the speaker driver based on a source signal for reproduction via the loudspeaker device;

determine a control current based on the target displacement of the diaphragm and a physical model of the loudspeaker device; and

transmit a control current signal specifying the control current to the current source amplifier, wherein the current source amplifier outputs the control current to drive the speaker driver based on the control current signal, and wherein an actual displacement of the diaphragm during the reproduction of the source signal is controlled based on the control current, via the control current signal.

18. The loudspeaker device of claim 17, wherein the physical model is a nonlinear model.

19. The loudspeaker device of claim 17, wherein the controller is further configured to:

monitor a voltage measured at terminals of the speaker driver during the reproduction of the source signal; and

provide updates of one or more loudspeaker model parameters for the loudspeaker device based on the measured voltage and one of the control current or the control current signal.

20. The loudspeaker device of claim 17, wherein:  
the control current limits the actual displacement of the diaphragm within a predetermined range of safe displacement and increases bass output at low frequencies; and  
a mechanical force applied on the diaphragm is based on an actual current output by the current source amplifier, the actual current based on the control current, and the actual current independent of one or more of the following nonlinear impedances: an electrical resistance of a driver voice coil of the speaker driver, or an inductance of the driver voice coil.

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